Sensitivity of dynamic responses of railway prestressed concrete sleepers with under sleeper pads to impact energy

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Abstract

In railway track, under sleeper pads (USPs) have recently been adopted as a resilient component placed underneath the concrete sleepers to moderate track stiffness. By the insertion, USPs are generally used to improve railway track resilience in special locations such as turnouts, bridge ends, viaducts, track transitions etc. However, railway tracks usually face high-intensity impact loading due to any imperfection of either wheel or rail. This paper presents a nonlinear 3D finite element model of prestressed concrete sleepers with under sleeper pads in to order to study the effect of USPs under high impact loading. This study has confirmed field studies that the sleepers with USPs tend to have lesser flexures, contact force and impact energy. However, this study reveals that the sleeper with USPs could be amplified by the large amplitude impact energy. These behaviours imply that the applications of USPs should be very careful since the USPs could trade off the desired benefits by aggravating dynamic behaviour of sleepers with under sleeper pads.

1 Introduction

Railway sleepers are a major structural component in ballasted railway tracks. The main functions of sleepers are to transfer train axle loads from the rails onto the underlying ballast bed and supporting system, and to secure rail gauge for safe passages of trains and rolling stocks. It has been noted that railway sleepers are safety-critical components [1, 2]. Generally, there are two groups of track components: superstructure and substructure. Superstructure components consist of rail, fastening system, sleeper and ballast, they sometimes include rail pad, under sleeper pad, and ballast mat. Substructure counterparts comprise subballast, formation, geotextiles and foundation [3, 4]. Under sleeper pads (USP) are resilient pads installed underneath the sleepers as an attachment to provide additional track resiliency between the sleepers and ballast. The typical cross section of the ballasted railway track with under sleeper pad is shown in figure 1. USP is often used in ballasted tracks with concrete sleepers. USP can also be applied in various operational environments such as conventional main lines, urban or high speed lines or light rail and metro lines. Nowadays, USP has been developed and used widely and heavily in central Europe such as in Austria, Czech Republic and Germany. Additionally, several counties have carried out pilot trials such as in Sweden, Australia, and China. USP is made of polyurethane elastomer with a foam structure including encapsulated air voids. USP is classified by the bedding modulus as very soft, soft, medium stiff and stiff USP [5-10]. Different types of USP can be used at different locations and for different purposes, as described in table 1.

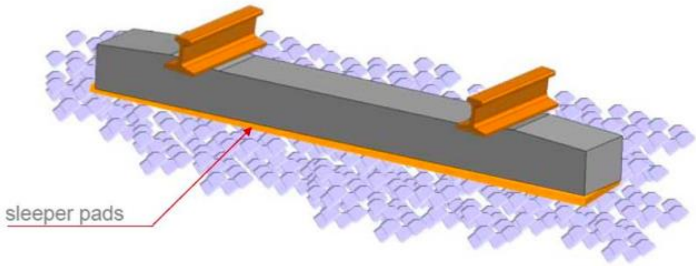


Figure 1: Typical ballasted railway track and its components with USP [1]

Table 1: USP applications and characterisations [11]

Fields of application of USP	USP			
	Very soft	Soft	Medium stiff	Stiff
	$C_{stat} \leq 0.10$	$0.10 < C_{stat} \leq 0.15$	$0.15 < C_{stat} \leq 0.25$	$0.25 < C_{stat} \leq 0.35$
Improve track quality (reduce ballast breakage and track/turnout pressure)				
Transition zones				
On existing structures with reduced ballast thickness				
Reduction of long-pitch low-rail corrugation in tight curves				
Reduction of ground-borne vibration				

The main objectives for using USP are to moderate track stiffness; to reduce ground borne vibrations; and to reduce ballast breakage [12-16]. USPs could reduce track stiffness in special areas such as turnout systems (switches and crossings) or bridge transitions. The vibration of sleepers could also be isolated by the USP so that the ballast and formation are uncoupled from the wheel/rail interaction, reducing the ground vibrations affecting surrounding areas and structures. The reduced ballast damage is accomplished by a reduction of contact pressure, and thus wears, in the sleeper/ballast interface. A more uniform load distribution is achieved by the use of USP, resulting in the reduction of the contact pressure and the smaller variations of support stiffness along the track. It was also noted that USP can lead to higher railway track economic values and to have substantial wider social benefits [17-20].

An application of USPs in Australia was initially trailed back in 1980s on open plain tracks. The outcome showed little improvement at the time whilst the delamination and degradation of the USP material were the key negative issues found in the field [21-28]. In recent years, the performance of the USPs has been improved through the outcomes from the test results in central Europe and in Austria, which show a promising quality and durability of USPs. Despite the benefits of USP have been presented [29], contradict outcome has been reported by Trafikverkets (Swedish Transport Administration). After several years of field inspections and observations, Trafikverkets reported that there has been no or very little influence of USPs on ballast size reduction and contamination resulting in track quality [30]. This could be a reason why the utilisation of USPs is not significant globally. Moreover, The USP has different effects on lateral track resistance. It cannot be confirmed whether positive or negative effects will occur at this stage. However, USP can lead to excessive sleeper vibration, resulting in ballast dilation or ballast spreading. Generally, railway track experience impact load, which is a shock load applied in short duration [2, 31]. The use of USPs for attenuating impact load and excessive vibration has been studied in the fields at specific locations such as dipped rails/welds, glue insulated joint etc [32-38]. However, the numerical studies into such the behaviour have been limited and not investigated.

The dynamic responses of railway concrete sleepers with under sleeper pads to high-intensity impact loading conditions are presented in this study. A three-dimensional finite element model has been established that can simulate and predict the responses of reinforced and prestressed concrete members. A three-dimensional nonlinear finite element model of a full-scale railway prestressed concrete sleeper for static analysis was firstly developed using the general-purpose finite element analysis package, ANSYS [39-41]. The static finite element model has been validated by the static full-scale experiment [41]. The experimental details were based on the European Standard [42]. The calibrated finite element model has been extended to include ballast support and in situ boundary conditions [43]. The extended model was linked to LS-Dyna for impact analysis. The impact analysis has been validated against the drop impact tests [44-46]. The initial velocities of drop mass corresponding to actual train load were applied to the rail. These can generate different impact energies. This study will focus on the sensitivity of impact energy to the dynamic responses of prestressed concrete sleepers with stiff USP. The dynamic responses including von mis stress, maximum displacements and accelerations of concrete sleepers with and without USP are highlighted.

2 Finite Element Modelling

Firstly, the general-purpose finite element analysis package, ANSYS was used to develop and model a three-dimensional finite element model of a full-scale railway prestressed concrete sleeper for static analysis. Concrete was modelled using SOLID65 solid elements where each node has three degree of freedom (trainslation in x,y and z). The modulus of elasticity of concrete (f'c) was estimated based on AS3600 [47] using the compressive strengths of 80 MPa. As for prestressing wire, LINK8 truss element was taken into account to withstand the initial strain attributed to prestressing forces, by assuming perfect bond between these elements and concrete. It should be note that this truss element cannot resist neither bending moments nor shear forces. Since bond slip is hardly observed under failure modes [48-50], the perfect bond between pre-stressing wires and concrete was assumed. The dynamic materials properties associated with strain rate of concrete and prestressing wires can be calculated. The 0.2% proof stress is 1,700 MPa and the ultimate stress is 1,930 MPa. The static and dynamic elasticity of moduli of pre-stressing wire are 190,000 MPa.

The extended finite element model was calibrated using vibration data [41, 49]. The updated finite element model was then transferred to LS-Dyna [45, 46], as shown in figure 2. The simulation results were achieved by assigning the initial velocity to the drop mass to generate an impact event, similarly to the actual drop tests. There are two cases considered in this study, 1.94m/s and 4.34 m/s. It is noted that these velocities are equivalent to the 600kg falling mass with the drop height of 0.2m and 1m, respectively. It is found that the finite element model is fairly sufficient for use in predicting impact responses of the prestressed concrete sleepers. The trends of peak acceleration responses are quite close to each other, although there is certain phase difference.

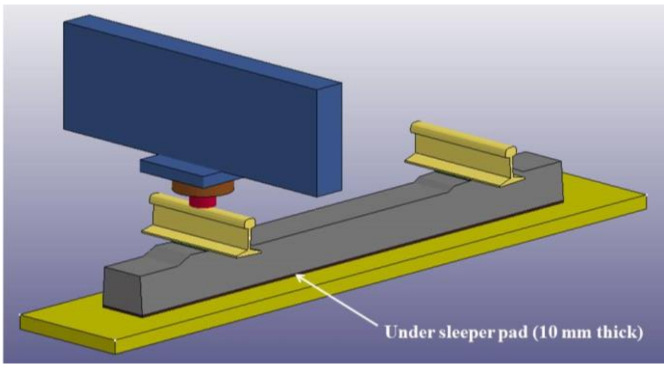


Figure 2: Finite element model of sleeper with under sleeper pad

3 Results and discussions

In this study, the stiff USP, which has the elastic modulus of 550MPa, is used. In this analysis, the initial velocities of 0.74m/s, 1.94m/s, 3.14m/s, 4.34m/s and 5.45m/s of drop mass are considered. Time histories of wheel-rail contact force are presented in figure 3. It is clearly seen that wheel-rail forces reduce significantly when using USP. It is interesting that pulse duration increases when USP is used because the support is softer. Thus, the support play a role on impact response as the impact magnitude decreases as the track stiffness, whilst, pulse duration is inversely proportional to the stiffness [50]. It should be note that the pulse durations are in the range of 3-4 ms. It is clearly seen that the use of USP can significantly reduce wheel/rail contact force by about 10%. The impact energy input is then calculated. It should be noted that the impulse is the area under the impact load history or the integral of force over the time. The different initial velocities of drop mass generate different impact energy. The impact energies of applied force to sleepers with and without USP are presented in table 2. It should be noted that even contact forces significantly reduce when using USP, the impact energies slightly decrease since pulse durations increase.

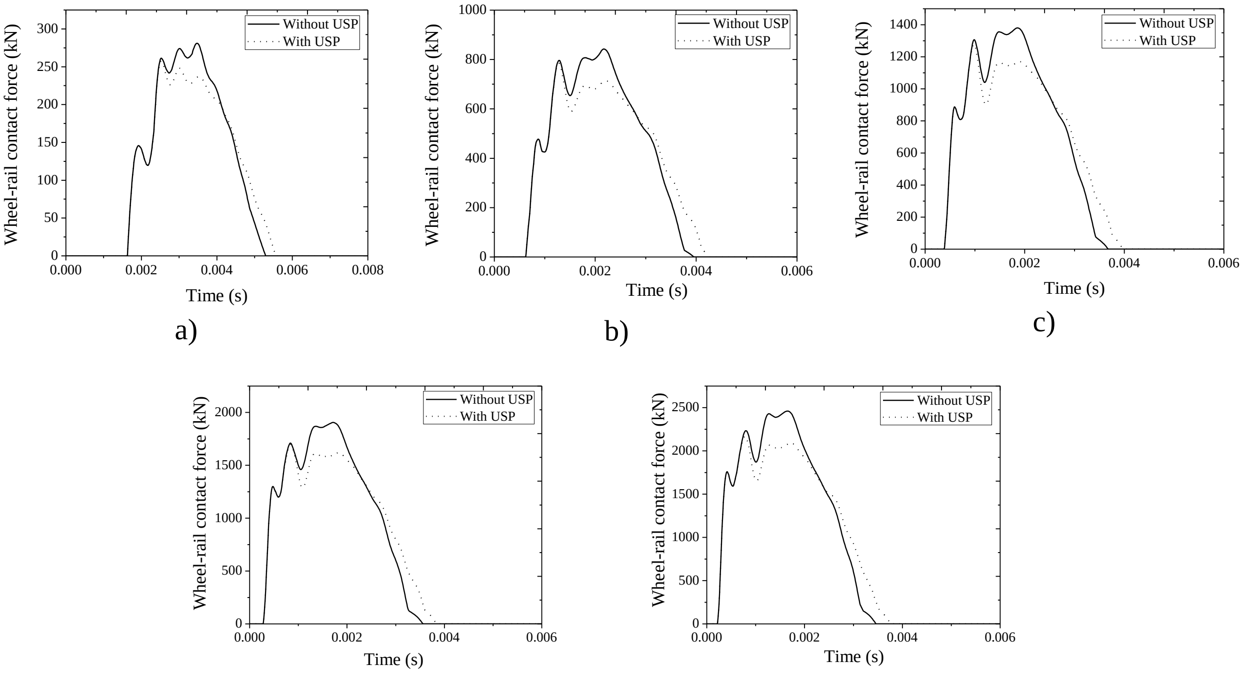
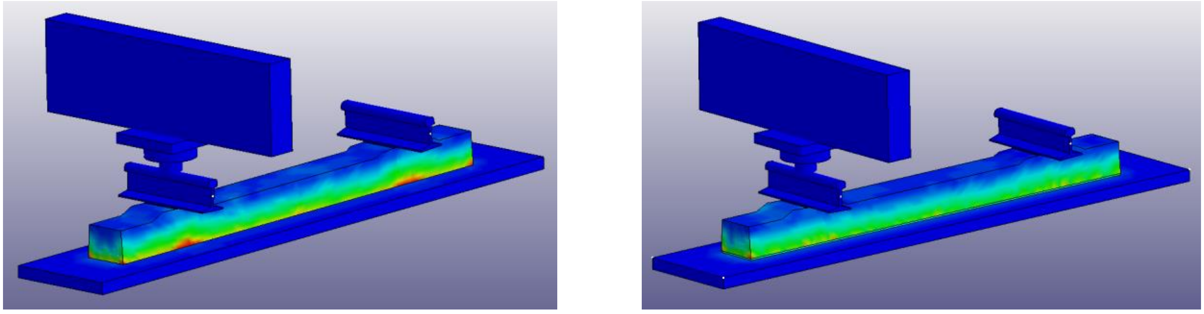


Figure 3: Wheel-rail contact force subjected to impact loads with the initial velocities of a) 0.74m/s b) 1.94m/s c) 3.14m/s d) 4.34m/s e) 5.54m/s

Table 2: Contact force and impact energy

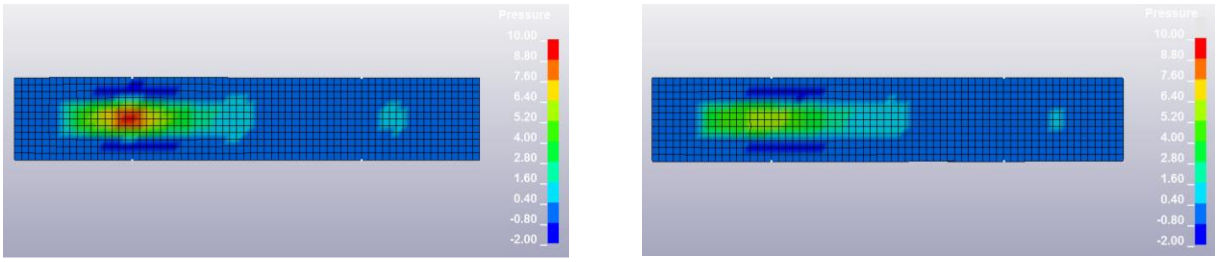
Case	Initial velocity (m/s)	Contact force (kN)		Impact energy (kNs)	
		Without USP	With USP	Without USP	With USP
A	0.74	288	258	647	639
B	1.94	843	785	1766	1755
C	3.14	1380	1279	2888	2866
D	4.34	1905	1699	4001	3974
E	5.54	2461	2171	5121	5066

Figure 4 shows the comparison of von mises stress contour between sleepers without and with USP before applying load. It is seen that the dynamic stress concentration on the concrete sleeper is less than that with USP especially at rail seat. Figure 5 illustrates the distribution of contact pressure on ballast under impact load case E. It is clearly seen that USP can significantly reduce the contact pressure especially at rail seat. This illustrates that USP can redistribute the impact load actions better along the concrete sleeper.



a) b)

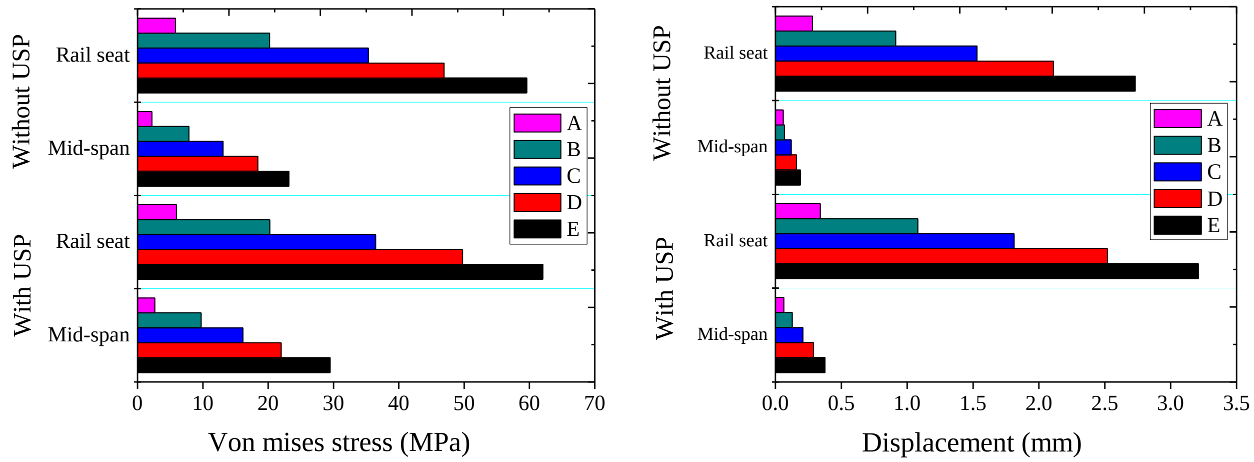
Figure 4: Von-mises stress contour of sleeper a) without USP b) with USP



a) b)

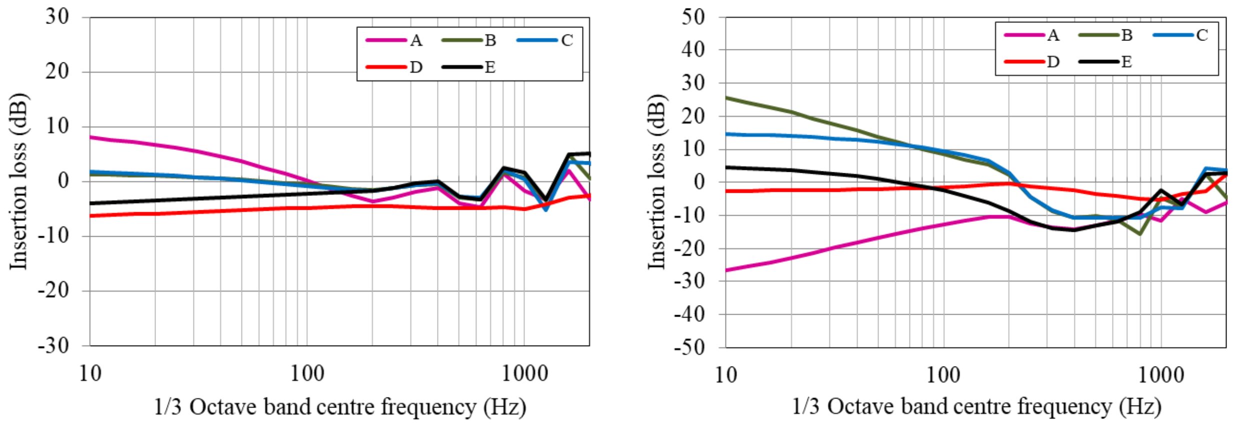
Figure 5: Contact pressure distribution on ballast a) without USP b) with USP under impact load

Figure 6 presents the effects of stiff USP on the dynamic responses of the concrete sleepers subjected to impact loads. Even though it is noticeable that the use of USP can obviously decrease the contact force and impact energy stress, von-mises stresses, displacements and accelerations of sleeper at both rail seat and mid-span slightly increase when using USP. USP has negative effect on sleeper maximum displacements at both rail seat and mid-span. It is interesting that about 30-40% increase of displacement at rail seat in all velocities are observed. This is because there is a reduction of concrete sleeper stiffness due to the adaptation of USP. This is confirmed by the previous field measurement conducted that the rise of sleeper vibration was observed when USP were taken into account. Although the impact force and impact energy reduce when using USP, the sleeper displacement slightly decreases. This is because the use of USP affects the overall track characteristics by reducing track stiffness and making track softer. This has more influence than impact force which leads to increase the sleeper displacement. The acceleration vibrations are also presented in term of insertion gain. Figure 7 demonstrates the insertion loss in concrete sleepers due to USP. It is clearly seen that USP can increase vibrations of concrete sleepers at both rail seat and mid-span. Thus, USPs tend to have large acceleration amplitude vibrations, especially when excited by a high-frequency impact force.



a) b)

Figure 6: Effects of USP on the maximum dynamic responses of railway concrete sleeper subjected to impact loads



a) b)

Figure 7: Insertion loss due to USP at a) rail seat b) mid-span

4 Conclusions

The emphasis of this study is placed on the effects of under sleeper pads on the dynamic responses of railway concrete sleeper subjected to high intensity impact loading. Finite element models of sleeper with USP have been conducted and analyzed using LS-DYNA. The initial velocities of drop mass are applied as an impact load. The models have been validated against the experimental results. The velocities applied to the mass corresponds to the drop mass of 600kg with the variations of height. The results show that the USPs will decrease stiffness of sleepers, then significantly reduce contact forces by about 10-30%. However, only the slight reductions of impact energy are observed in all cases. This is because the pulse duration may increase when using USPs which can increase the impact energy even the contact forces reduce. Although the studies have found that the sleepers with USPs tend to have lesser flexures, contact forces, this numerical study and previous field data also confirm that a railway track with USPs could experience a large displacement and acceleration amplitude vibrations, especially when excited by a high-frequency impact force. It can be concluded that the use of USPs should be very careful since the USPs may have a trade-off impact that could aggravate dynamic behaviour of sleepers with under sleeper pads.

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References

[1] S. Kaewunruen, A.M. Remennikov, *Non-destructive testing (NDT): A tool for dynamic health monitoring of railway track structures*, Materials Australia, Vol. 39, No. 6, (2006).

[2] A.M. Remennikov, S. Kaewunruen, *A review on loading conditions for railway track structures due to train and track vertical interaction*, Structural Control and Health Monitoring, Vol. 15, (2008), pp. 207-234.

[3] B. Indraratna, C. Rujikiatkamjorn, W. Salim, *Advanced Rail Geotechnology – Ballasted Track*, CRC Press, London, UK (2011).

[4] C. Ngamkhanong, S. Kaewunruen, C. Baniotopoulos, *A review on modelling and monitoring of railway ballast*, Structural Monitoring and Maintenance, vol. 4, (2017), pp. 195-220.

[5] A. Johansson, J.C.O. Nielsen, R. Bolmsvik, A. Karlström, *Under sleeper pads – influence on dynamic train-track interaction,* Wear, Vol. 265, (2008), pp. 1479–687.

[6] International Union of Railway, *USP Report, Under sleeper pads*, Project no. I/05/U/440, Summarising report, (2009).

[7] International Union of Railway, *USP recommendations, Under Sleeper Pads, Recommendations for Use*, UIC-Leaflet, Draft Document, (2013).

[8] R. Schilder, *USP-under sleeper pads, Applications and benefits of elastic elements in ballasted tracks,* UIC project no. I/05/U/440, Paris 17 (2006)

[9] J. Jenkins, S. Stephenson, G. Clayton, G. Morland, D.L. Lyon, *Incidences des paramètres caracteristiques de la voie et des vehicules sur les efforts dynamics verticaux qui se développent entre rail et roue*, Rail International, Vol. 3, No. 10, 1974, pp. 682-702.

[10] S. Lakuši, M. Ahac, I. Haladin, *Experimental investigation of railway track with under sleeper pad,* 10th Slovenian road and transportation congress, Portorozˇ, Slovenija (2010).

[11] International Union of Railway, *UIC Leaflet 917 Guidelines for under sleeper pad,* Paris, France, 2015.

[12] T. Dahlberg, *Railway track stiffness variations-consequences and countermeasures*, Int. J. Civ. Eng., Vol. 8, No. 1, 2010, pp. 1–12.

[13] P. Schneider, R. Bolmsvik, J.C.O. Nielsen, *In situ performance of a ballasted railway track with under sleeper pads*, J. Rail Rapid Transit,Vol. 225, No. 3, 2011, pp. 299-309.

[14] W. Stahl, *Improvement of ballasted tracks using sleeper pads – investigations and experiences in Germany*, Munich University of Technology (2004).

[15] F. Müller-Boruttau, U. Kleinert , *Betonschwellen mit elastischer Sohle*, ETR, Vol. 50, No. 3, (2001).

[16] V.L. Marine, M.J.M.M. Steenburgen, I.Y. Sheets, *Combating RCF on switch points by tuning elastic track properties*, Wear, Vol. 271, No. 1, (2009), pp. 158-167.

[17] S. Setsobhonkul, S. Kaewunruen, J.M. Sussman, *Lifecycle Assessments of Railway Bridge Transitions Exposed to Extreme Climate Eventsm*, Front. Built Environ., vol. 3, 2017.

[18] C. Nhamkhanong, A.T. Nascimento, S. Kaewunruen, *Economics of track resilience*, World

Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium, IOP Conference Series: Material Science and Engineering, 2018 (accepted).
[19] A. Ortega, S. Blainey, J. Preston, *Installation of under sleeper pads on ballasted railway tracks: An economic analysis of their potential implementation*, Proc IMechE, Part F: J Rail and Rapid Transit, (2017).
[20] M.H. Bin Osman, S. Kaewunruen, *Uncertainty Propagation Assessment in Railway-Track Degradation Model Using Bayes Linear Theory*, Journal of Transportation Engineering, Part A: Systems, Vol. 144, No. 7, (2018).
[21] S. Kaewunruen, A. Aikawa, A.M. Remennikov, *Vibration attenuation at rail joints through under sleeper pads*, Procedia Engineering, Vol. 189, (2017), pp. 193-198.
[22] S. Kaewunruen, J.M. Sussman, H.H. Einstein, *Strategic framework to achieve carbon-efficient construction and maintenance of railway infrastructure systems*, Frontiers in Environmental Sciences, Vol. 3, No, 6, (2015).
[23] S. Nimbalkar, B. Indraratna, S.K. Dash, D. Christie, *Improved performance of railway ballast under impact loads using shock mats*, ASCE Journal of Geotechnical & Geoenvironmental Engineering, Vol. 138, No. 3, (2012), pp. 281-294.
[24] S. Kaewunruen, A.M. Remennikov, *Under sleeper pads: field investigation of their role in detrimental impact mitigation*, Proceedings of the 13th International Railway Engineering Conference, Edinburgh, UK, 2015 June 30 - July 1.
[25] P. Schneider, R. Bolmsvik, J.C.O. Nielsen, *In-situ performance of a ballasted railway track with under sleeper pads*, Journal of Rail and Rapid Transit, Vol. 225, No. 3, (2011), 299-309.
[26] UIC: International Union of Railway, *UIC Leaflet: Guideline for Under Sleeper Pads*, Paris, France (2014).
[27] M.V. Tuler, S. Kaewunruen, *Life cycle analysis of mitigation methodologies for railway rolling noise and groundbourne vibration*, Journal of Environmental Management, Vol. 191, (2017), pp. 75-82.
[28] R. Tavares de Freitas, S. Kaewunruen, *Life cycle cost evaluation of noise and vibration control methods at urban railway turnouts*, Environments, Vol. 3, No. 4, (2016), pp. 34.
[29] R. Schilder, *USP (under sleeper pads) – a contribution to save money in track maintenance*, in AusRAIL PLUS (Sydney: AusRAIL PLUS), (2013).
[30] B. Larsen, *Under Sleeper Pads on the Ofoten Line*, Proceedings of the 19th Nordic Seminar on Railway Technology, Luleå, Sweden (2016).
[31] C. Ngamkhanong, S. Kaewunruen, B.J.A. Costa, *State-of-the-Art Review of Railway Track Resilience Monitoring*, *Infrastructures*, Vol. 3, (2018).
[32] A. Paixão, J.N. Varandas, E. Fortunato, R. Calçada, *Numerical simulations to improve the use of under sleeper pads at transition zones to railway bridges*, Engineering Structures, Vol. 164, (2018), pp.169-182.
[33] H. Li, G.R. McDowell, *Discrete element modelling of under sleeper pads using a box test*, Granular Matter, Vol.20, No. 2, (2018), pp. 2-26.
[34] L. Le Pen, G. Watson, A. Hudson, W. Powrie, *Behaviour of under sleeper pads at switches and crossings–Field measurements,* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Vol. 232, No. 4, (2018), pp. 1049-1063.
[35] S. Kaewunruen, *Discussion of "Mitigation of Ground Vibration Generated by High-Speed Trains on Saturated Poroelastic Ground with Under-Sleeper Pads"*, ASCE Journal of Transportation Engineering, Vol. 141, No. 1, (2015).
[36] J. Mottahed, J.A. Zakeri, S. Mohammadzadeh, *Field and numerical investigation of the effect of under-sleeper pads on the dynamic behavior of railway bridges*, Proc IMechE, Part F: J Rail and Rapid Transit, in press, (2017).
[37] J.A. Zakeri, M. Esmaeili, H. Heydari-Noghabi, *A field investigation into the effect of under sleeper pads on the reduction of railway-induced ground-borne vibrations*, Proc IMechE, Part F: J Rail and Rapid Transit, Vol. 230, (2016), pp. 999–1005.
[38] S. Kaewunruen, T. Ishida, A.M. Remennikov, *Dynamic Performance of Concrete Turnout Bearers and Sleepers in Railway Switches and Crossings*, Advances in Civil Engineering Materials, (2018) doi.org/10.1520/ACEM20170103. ISSN 2379-1357.

[39] S. Kaewunruen, A.M. Remennikov, *Effect of a large asymmetrical wheel burden on flexural response and failure of railway concrete sleepers in track systems*, Engineering Failure Analysis, Vol. 15, No. 8, (2008), pp. 1065-1075.
[40] S. Kaewunruen, A.M. Remennikov, *Experimental simulation of the railway ballast by resilient materials and its verification by modal testing*, Experimental Techniques, Vol. 32, No. 4, (2008), pp. 29-35.
[41] S. Kaewunruen, A.M. Remennikov, *Nonlinear finite element modeling of railway prestressed concrete sleeper*, *Proceedings of the 10th East Asia-Pacific Conference on Structural Engineering and Construction, EASEC*, Vol. 4, (2006), pp. 323-328.
[42] S. Kaewunruen, and A.M. Remennikov, *Experimental and numerical studies of railway prestressed concrete sleepers under static and impact loads*, Civil Computing, Vol. 3, (2007), pp. 25-28.
[43] E.K. Gamage, S. Kaewunruen, A.M. Remennikov, T. Ishida, *Toughness of Railroad Concrete Crossties with Holes and Web Openings*. Infrastructures, Vol. 2, No. 3, (2017).
[44] E.K. Gamage, S. Kaewunruen, A.M. Remennikov, T. Ishida, *Reply to Giannakos, K. Comment on: Toughness of Railroad Concrete Crossties with Holes and Web Openings*. Infrastructures, Vol 2, No. 5, (2017).
[45] British Standards Institute (BSI), *European Standard BS EN13230 Railway applications*. Track. Concrete sleepers and bearers, London UK, (2016).
[46] S. Kaewunruen, A.M. Remennikov, *Low-velocity impact analysis of prestressed concrete sleepers. Concrete Institute of Australia's 23rd Biennial Conference 07, October 18-20, Adelaide, Australia,* (2007).
[47] S. Kaewunruen, A.M. Remennikov, "Impact responses of prestressing tendons in railway concrete sleepers in high speed rail environmen*ts." Proceedings of the 5th Computational Methods in Structural Dynamics and Earthquake Engineering, May 25-27, Crete Island, Greece,* (2015).
[48] S. Kaewunruen, A.M. Remennikov, S. Minoura, *Dynamic responses of railway ultra-high-strength concrete sleepers under extreme impact loading*. *Proceedings of the 6th Computational Methods in Structural Dynamics and Earthquake Engineering, June 15-17, Rhodes Island, Greece,* (2017).
[49] Standards Australia, *Design of concrete structures*, Australian Standard: AS3600-2001, (2001).
[50] Z. Cai, *Modelling of rail track dynamics and wheel/rail interaction*, PhD Thesis, Department of Civil Engineering, Queen's University, Ontario, Canada (1992).
[51] S. Kaewunruen, M.J. Sussman, M Akira, *Grand Challenges in Transportation and Transit Systems*. Frontiers in Built Environment, Vol. 2, (2016).